Nanoscale Hot-Wire Anemometer Probe with Contoured Silicon Probe Body

CNF Project Number: 2532-17

Principal Investigator(s): Gregory P. Bewley

User(s): Edmund T. Liu

Affiliation(s): The Sibley School of Mechanical and Aerospace Engineering, Cornell University

Primary Source(s) of Research Funding: The Sibley School of Mechanical and Aerospace Engineering, Cornell University

Contact(s): GPB1@cornell.edu, ETL46@cornell.edu

Primary CNF Tools Used: Heidelberg mask writer - DWL2000, SÜSS MA-6, Oxford PECVD, CVC SC4500 odd-hour evaporator, Oxford 82, Plasma-Therm Versaline deep silicon etcher, Unaxis 770 deep silicon etcher

Abstract:

Turbulence measurements are difficult to take due to the large separation of scales present in a flow. At the smallest scales, where conventional probes are limited by spatial and temporal resolution, measurements are a result of the physical dimensions and thermal mass of the sensing element. Semiconductor fabrication equipment enables the manufacturing of hot-wires much smaller than their conventional counterparts in volume, driving down costs while increasing measurement sensitivity. We report on the successful creation of such a probe with a sensing element measuring 60 × 2 × 0.1 μm supported by a contoured silicon body. The probe is compared to a conventional probe 1.27 μm in diameter in jet turbulence generated by a calibration tank and exhibits higher temporal resolution. The high-throughput process is found to have a yield rate > 95%.

Summary of Research:

Hot-wire anemometry is a method to measure flow velocities and is commonly used for turbulent flows due to high frequency response, spatial resolution, and ease of use. Hot-wires operate by heating up a small wire with electrical current. Placed in a flow, generated heat is convected from the wire to the fluid, with higher flow velocities corresponding to greater amounts of heat convection. By exploiting the wire material's temperature-dependent resistance, the measured voltage across the wire is correlated to the flow velocity.

Sensor performance is significantly impacted by the physical dimensions and material of the wire. Smaller wires exhibit high frequency response due to a small thermal mass, and shorter lengths lead to less spatial filtering. Moreover, a large length-to-diameter ratio is desired to mitigate the effects of end-conduction, where generated heat is conducted to the wire supports, rather than convected to the flow of interest. The smallest conventional wires available measure 0.6 to 1.27 μm in diameter and require labor-intensive soldering and chemical etching, thereby limiting probe throughput. Semiconductor manufacturing equipment is promising because it allows for the fabrication of sensing elements unachievable by conventional means at high-throughput and repeatability. On a single 4-inch wafer, hundreds of such probes may be created.

Initial work on hot-wire probes manufactured with semiconductor processing equipment was performed at Princeton University, resulting in the development of the nanoscale thermal anemometry probe (NSTAP) [1]. Unlike the sharp features used in the NSTAP, we designed a contoured metal film and probe body using AutoCAD and MATLAB. Original NSTAP processes relied on deep reactive-ion etching (RIE) and exploited RIE-lag to produce a 3D aerodynamic probe body. A similar process is used to create in-house probes.

First, 500 nm and 4 μm of silane-based silicon dioxide is formed through plasma-enhanced chemical vapor deposition (PECVD) on either side of a double-side polished wafer with the Oxford PECVD. 100 nm of platinum with a 10 nm titanium adhesion layer is then evaporated onto the 500 nm oxide and lifted off with a LOR bi-layer exposed with the SÜSS MA-6 contact aligner. On the backside, a fine pattern consisting of trenches used to induce RIE-lag is transferred from a SPR220-3.0 photoresist softmask to the 4 μm oxide to form a hardmask. Softmask exposure is performed with the MA-6 in vacuum contact mode, and the hardmask is etched with the Oxford PlasmaLab 82. Through-wafer etching is then performed with both the Plasma-Therm VersaLine and the Unaxis 770 deep silicon etchers, and the profile is smoothed with isotropic silicon etching. Finally, the remaining 500 nm oxide layer is etched to release the probes and free-standing platinum wire.

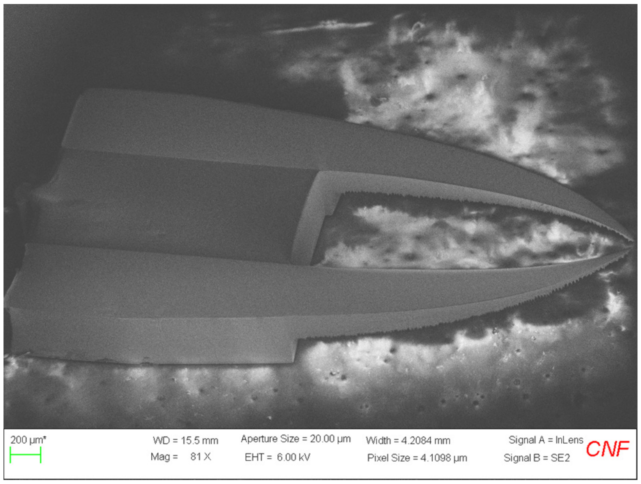

Figure 1: Probe following release from the wafer. The platinum trace and supporting silicon body are contoured, and the three-dimensional taper, a result of RIE-lag, is visible.

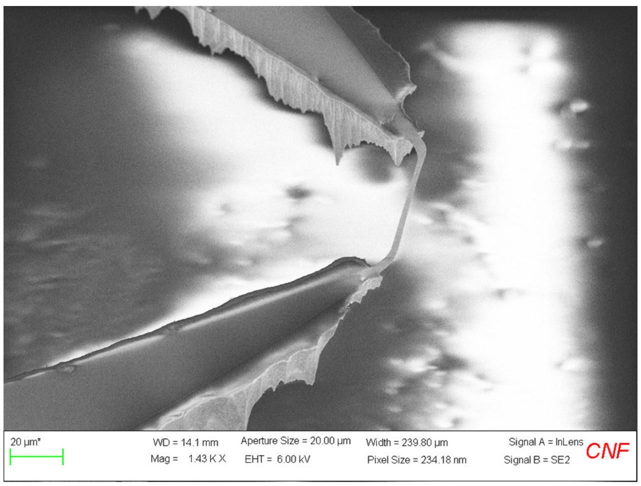

Figure 2: Magnified SEM image of the thin free-standing platinum wire.

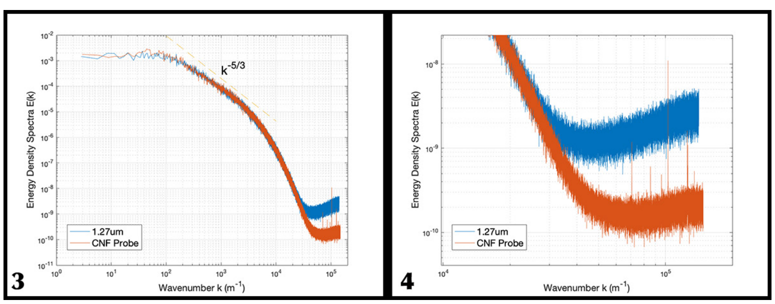

Figure 3, left: Comparison of turbulent spectra from a jet measured with a CNF probe and conventional 1.27 µm hot-wire. We observe a high degree of agreement in the collected spectra. Figure 4, right: Magnified image of the high-frequency spectra. Compared to the conventional hot-wire, the CNF probe is able to resolve more of the dissipation range. The spectra appear to flatten at higher frequencies, most likely due to the noise floor of external electronics.

Figures 1 and 2 show the final probe following release from the wafer and a magnified image of the free-standing wire, respectively. The tapered profile created using RIE-lag is visible and extends downstream from the wire, where there is minimal supporting silicon. The probe is verified using jet turbulence produced by a calibration tank. Placed about twelve opening diameters away from the jet outlet, the probe successfully measures a turbulent spectra, with high agreement with a conventional 1.27 μm hot-wire as shown in Figure 3.

Looking more closely at the high-frequency components of the spectra, we see that the microfabricated probe resolves even more of the dissipation range.

References:

[1] Vallikivi M. and Smits A.J., "Fabrication and Characterization of a Novel Nanoscale Thermal Anemometry Probe," Journal of Microelectromechanical Systems, vol. 23, no. 4, pp. 899-907, Aug. 2014, doi: 10.1109/JMEMS.2014.2299276.